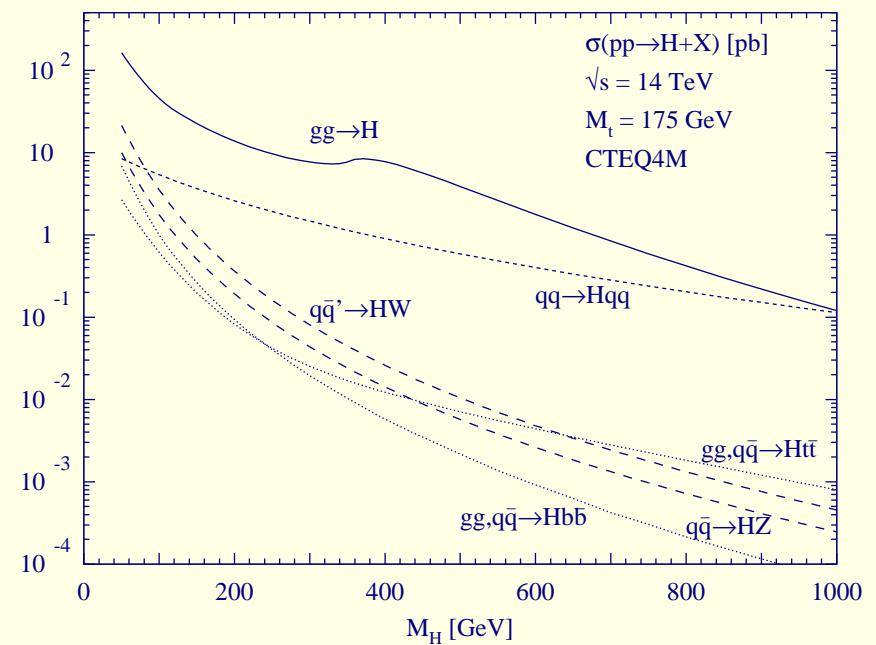
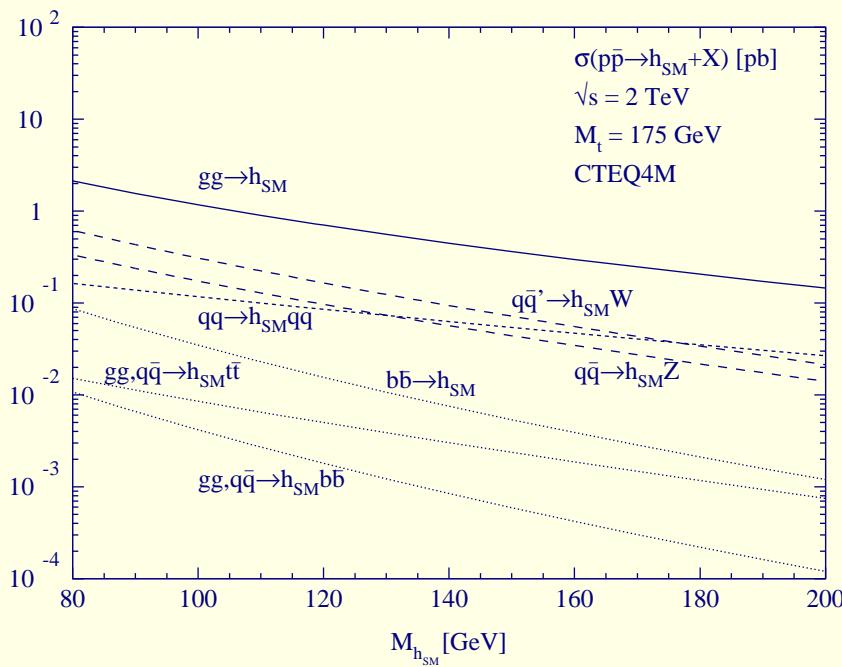


Higgs Boson Production with Bottom Quarks at Hadron Colliders

Chris Jackson (Florida State University)
DPF2004, August 2004

with S. Dawson (BNL), L. Reina (FSU), and D. Wackerlo (SUNY-Buffalo)

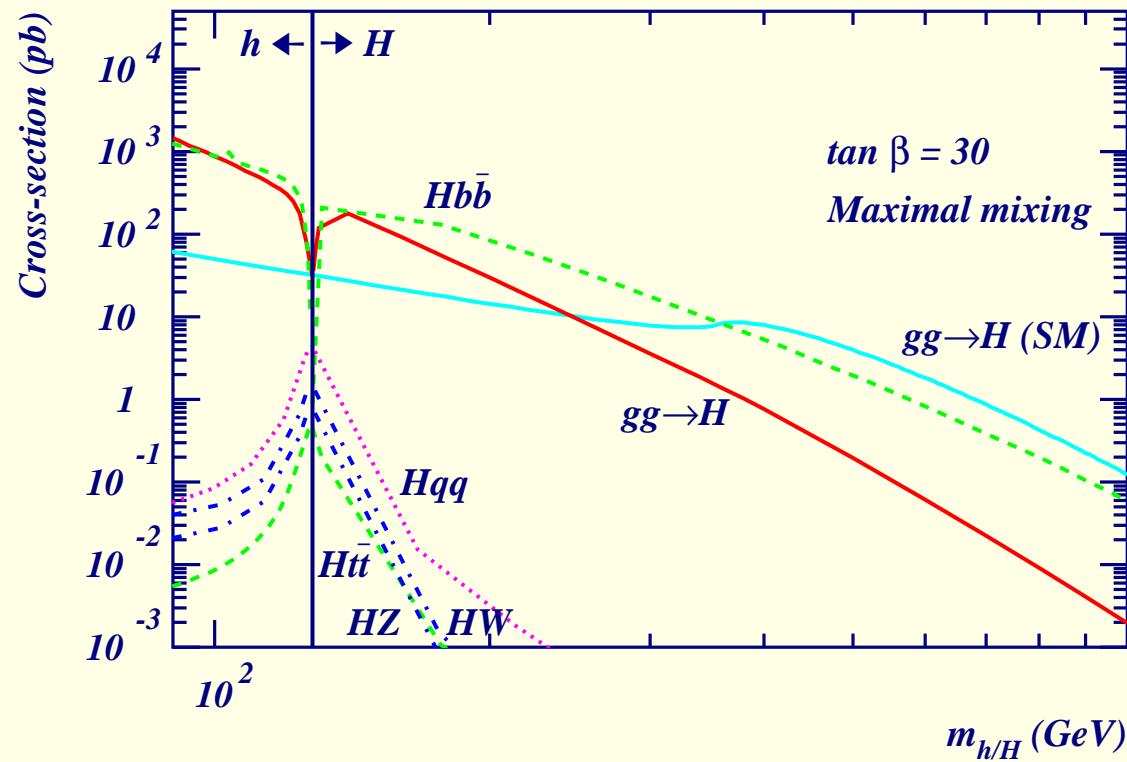
SM Higgs Production at Hadron Colliders



(from M. Carena, H. Haber, Prog.Part.Nucl.Phys.50(2003))

- In **SM**, Higgs production dominated by $gg \rightarrow h$
- $b\bar{b}h$ suppressed due to smallness of $g_{hb\bar{b}} \sim \frac{m_b}{v}$

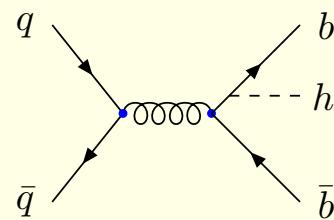
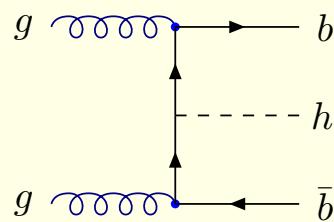
MSSM Higgs Production at Hadron Colliders



(from M. Carena, H. Haber, Prog.Part.Nucl.Phys.50(2003))

- Yukawa coupling enhanced: $g_{bb(h^0,H^0)}^{MSSM} = \frac{(-\sin \alpha, \cos \alpha)}{\cos \beta} g_{bbh}$
- $\sigma_{(h^0,H^0)b\bar{b}}$ comparable or larger than $\sigma_{gg \rightarrow (h^0,H^0)}$

Four Flavor Number Scheme (4FNS)

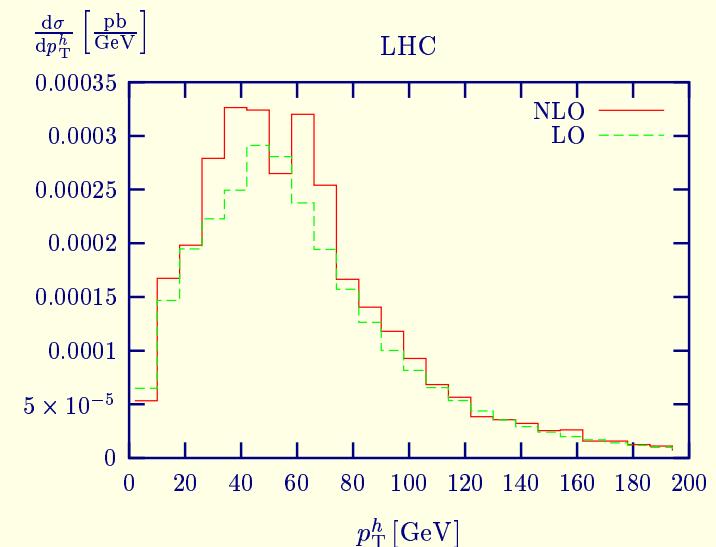
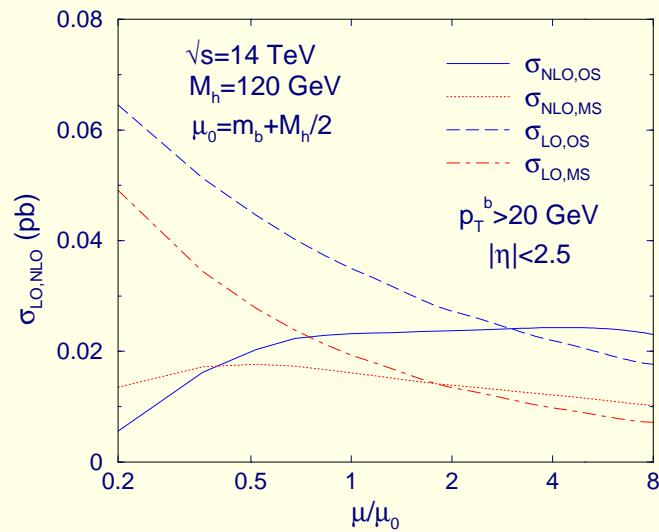
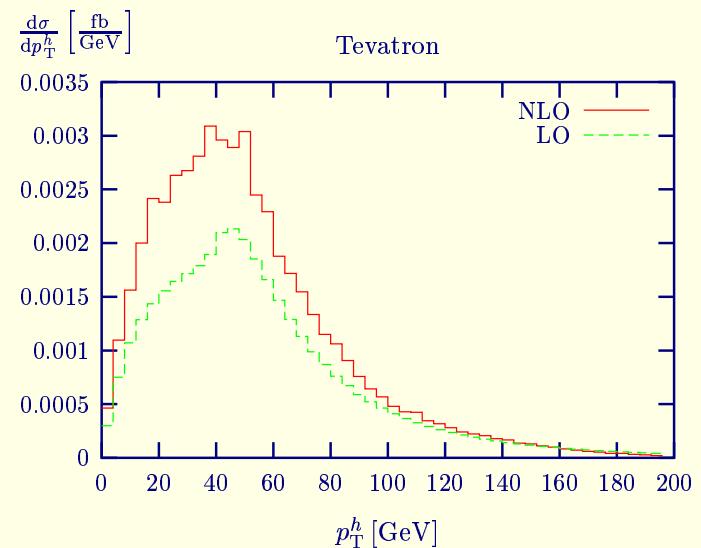
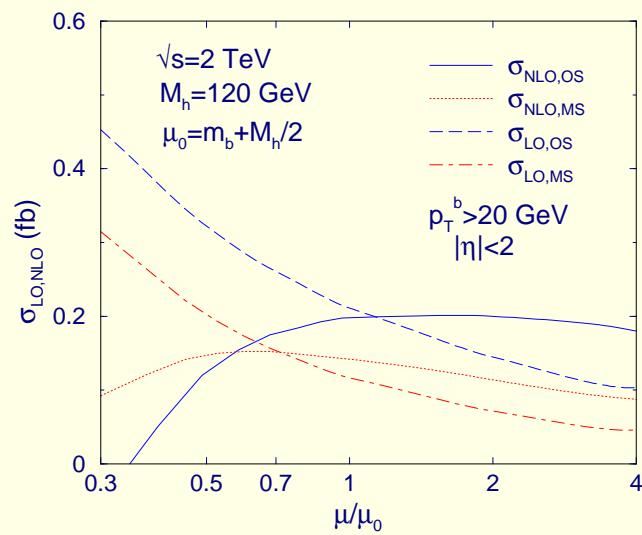


- Tagging b jets:
 - **inclusive** \equiv no cuts on p_T of b 's
 - **semi-inclusive** \equiv one high- p_T b
 - **exclusive** \equiv two high- p_T b 's
- (Semi-)Inclusive c.s. develops potentially large log's ($\Lambda_b \equiv \log(\frac{Q^2}{m_b^2})$) from collinear splitting ($g \rightarrow b\bar{b}$)
- Perturbative expansion: $\alpha_s \rightarrow \alpha_s \Lambda_b$

Exclusive $b\bar{b}h$ Production

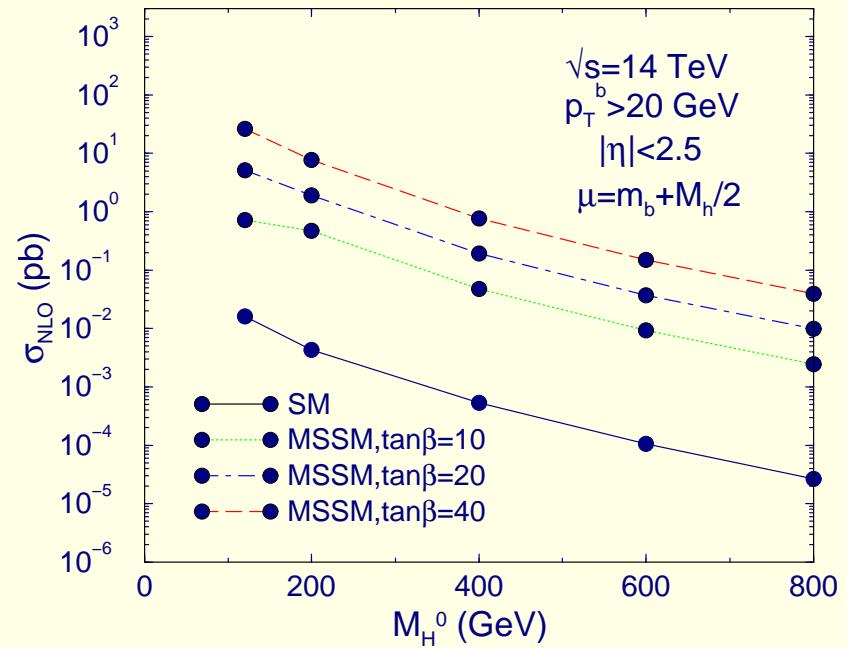
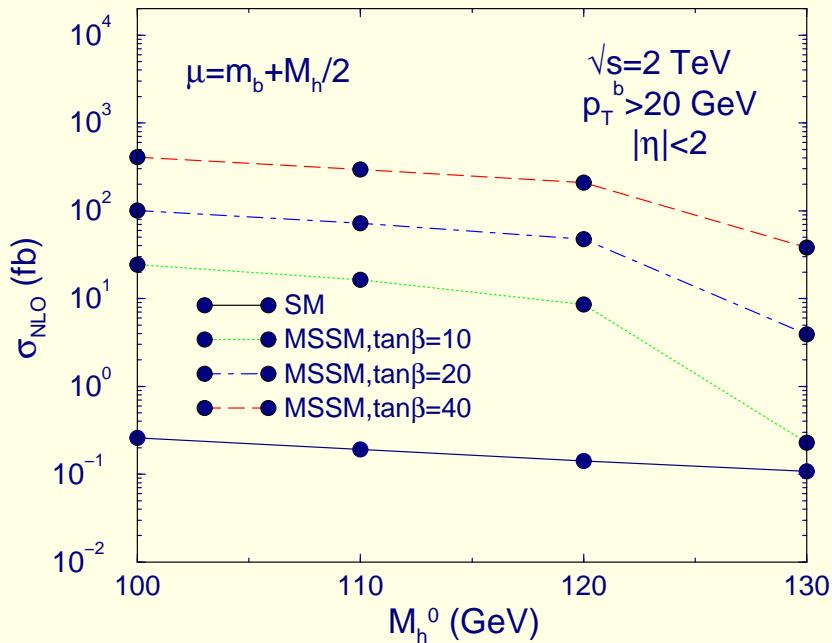
- Two independent calculations of NLO QCD corrections:
 - S. Dittmaier, M. Kramer, M. Spira (hep-ph/0309204)
 - S. Dawson, C.J., L. Reina, D. Wackerlo (PRD 69 074027 (2004))
- Setup:
 - Require two high- p_T b jets in final state: $p_T^{b,\bar{b}} > 20$ GeV and $|\eta_{b,\bar{b}}| < 2(2.5)$ Tevatron (LHC)
 - Radiated g and b/\bar{b} distinct only if $\Delta R > 0.4$
- Cuts reduce signal and background
- Factorization/renormalization scale dependence reduced
- Given large sensitivity of $m_b(\mu_r)$ on μ_r , also investigated renormalization scheme dependence for m_b
 - OS vs. \overline{MS} : at $\mathcal{O}(\alpha_s^3)$ both are perturbatively consistent
 - Difference being at higher orders → theoretical uncertainty $\approx 15 - 20\%$

Results for Exclusive $b\bar{b}h$ Production



(from S. Dawson, C.J., L. Reina and D. Wackerlo, PRD 69, 074027 (2004)))

$M_H, \tan \beta$ Dependence for Exclusive $b\bar{b}(h^0, H^0)$



(from S. Dawson, C.J., L. Reina, D. Wackerloher ,PRD 69,074027 (2004))

- Large $\tan \beta \rightarrow$ top loop suppressed
- Good approximation: $\sigma_{NLO}(\text{MSSM}) \sim \sigma_{NLO}(\text{SM}) \left(\frac{g_{bbh}^{\text{MSSM}}}{g_{bbh}^{\text{SM}}} \right)^2$

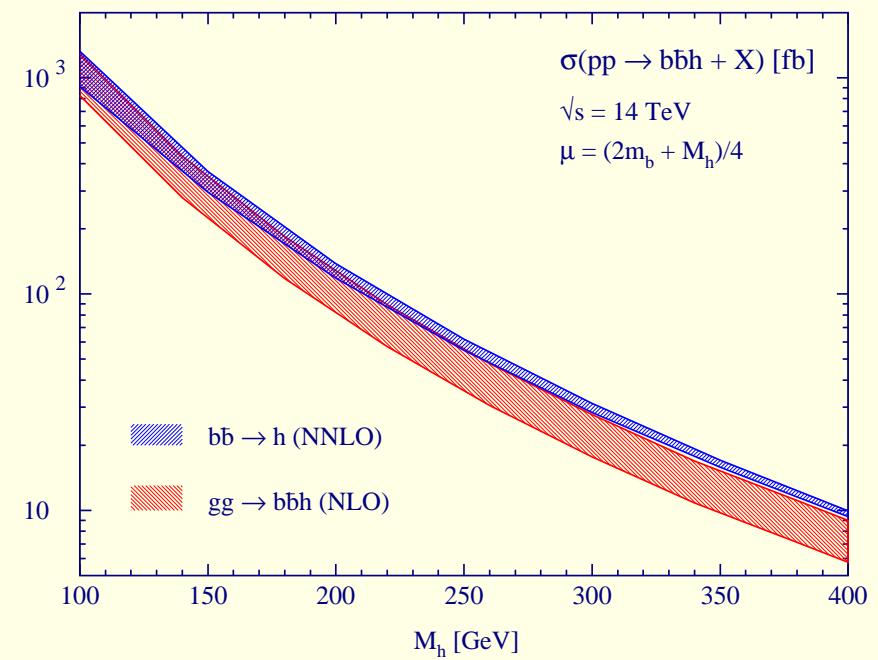
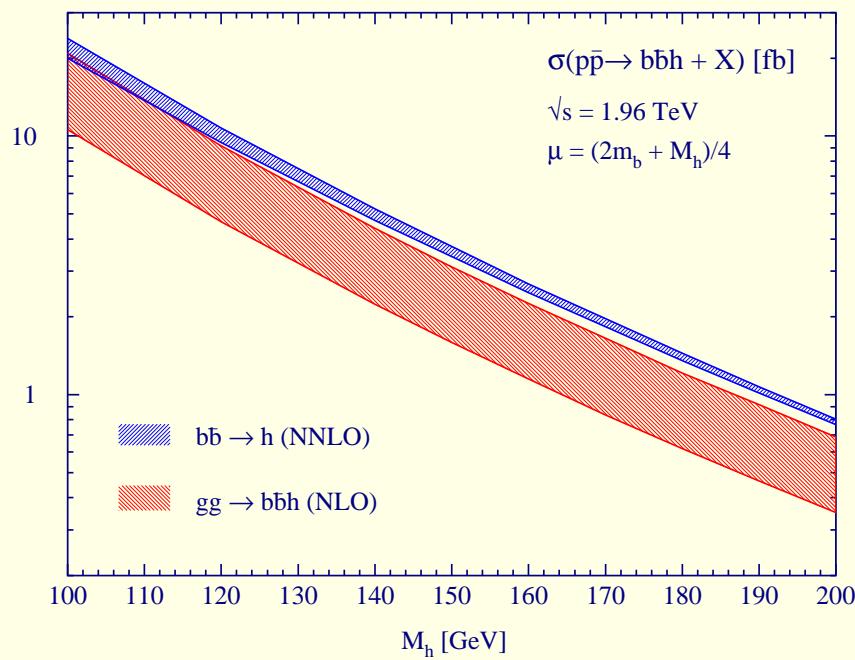
Five Flavor Number Scheme (5FNS)

- Physical process $gg \rightarrow b\bar{b}h$ contains large logs from (**collinear**) splitting $g \rightarrow b\bar{b}$
- Introduce (theoretically defined) ***b*-quark PDF**:

$$\tilde{b}(x, \mu) = \frac{\alpha_s(\mu)}{2\pi} \log\left(\frac{\mu^2}{m_b^2}\right) \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y, \mu)$$

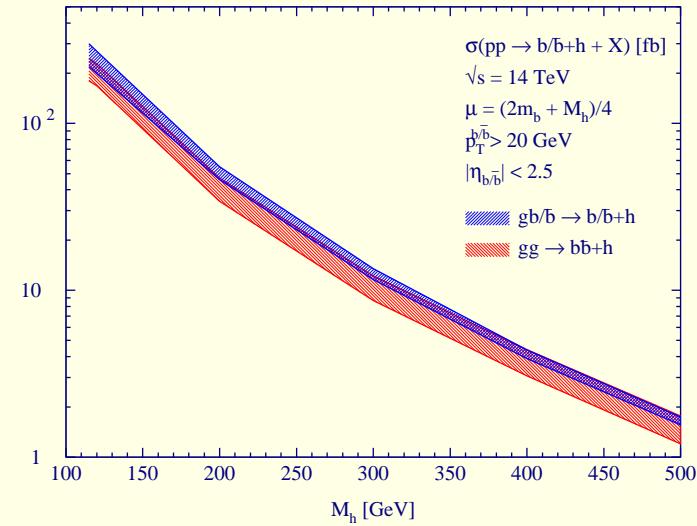
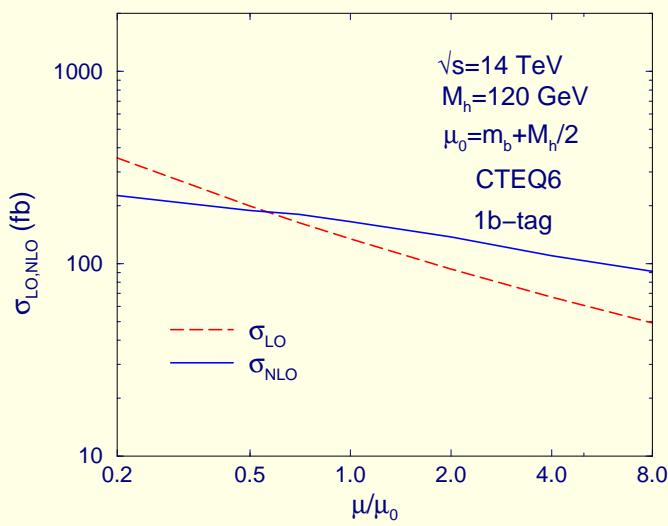
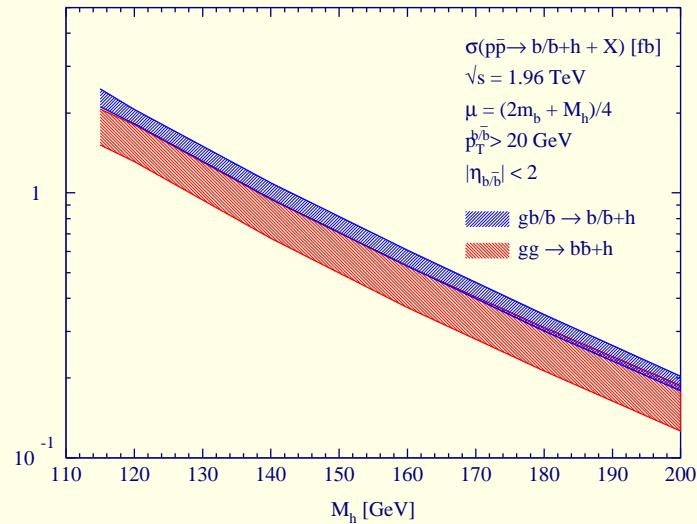
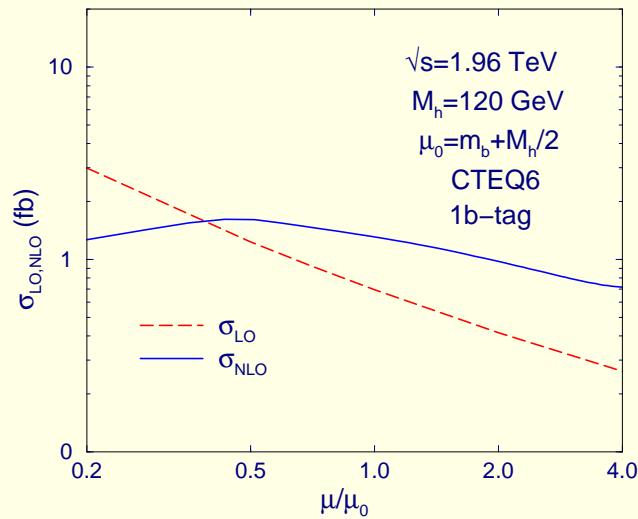
- Leading Processes in 5FNS:
 - **Inclusive** $\equiv b\bar{b} \rightarrow h$ (Known at NNLO (see Harlander & Kilgore PRD 68 (2003) 013001))
 - **Semi-inclusive** $\equiv gb \rightarrow bh$ (Known at NLO (see Campbell et.al PRD 67 (2003) 095002))
- Important to study **validity/compatibility** of 4FNS/5FNS

Results for Inclusive $(b\bar{b})h$ Production



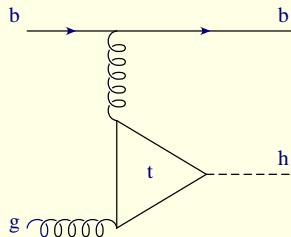
(from J. Campbell et. al. (Higgs Working Group), Les Houches workshop on Physics at TeV Colliders (2004), hep-ph/0405302)

Results for Semi-inclusive $b(\bar{b})h$ Production



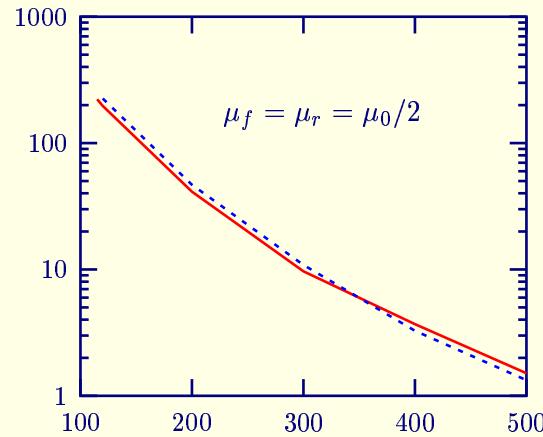
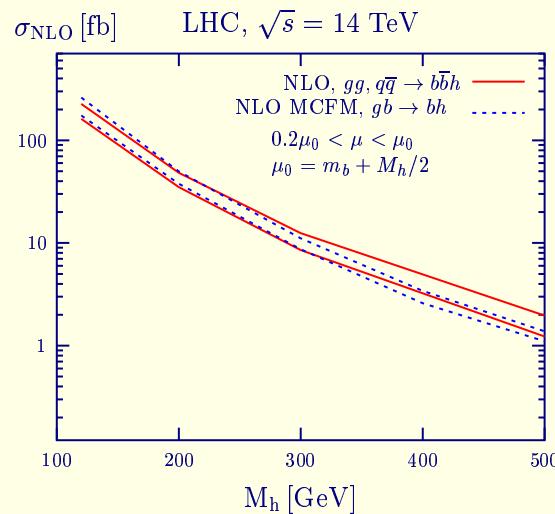
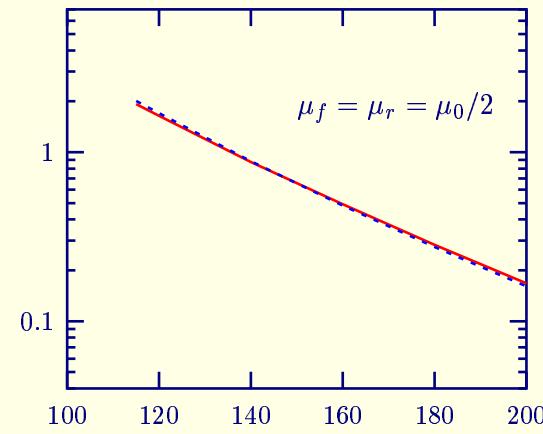
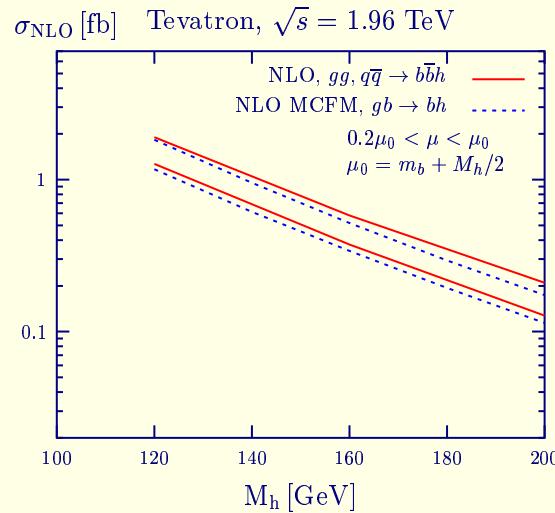
Not the End of the Story

- Diagrams containing loops of quarks **neglected** in 5FNS



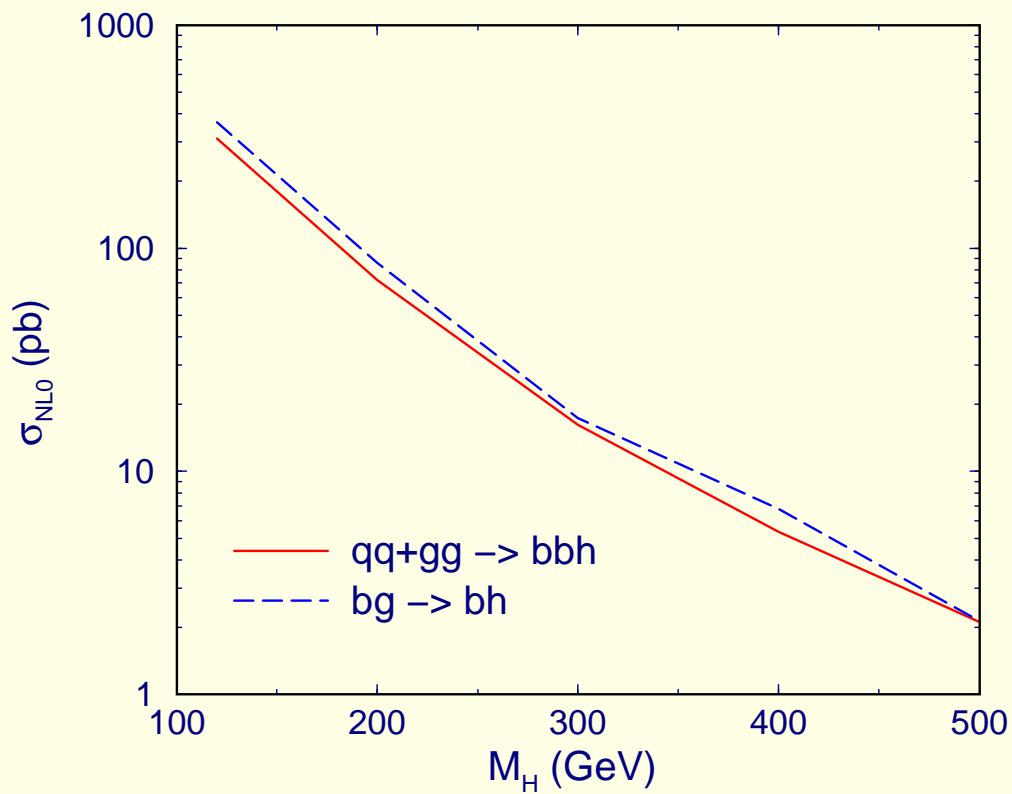
- $bg \rightarrow bh$ @ NLO performed in the $m_b = 0$ approximation (except in g_{hbb}):
 - Top quark loop neglected since $g_{(h^0, H^0)tt}^{MSSM} \sim \frac{1}{\tan \beta}$
 - Bottom quark loop neglected since amplitude is $\propto m_b$
 - In SM, this diagram (w/ top quarks) makes a contribution $\sim \mathcal{O}(g_{Hbb}^2) \rightarrow$ **could be numerically important!**
- To compare 4FNS and 5FNS for semi-inclusive process, we utilized **MCFM** (Campbell and Ellis, webpage:mcfm.fnal.gov) **altered** to contain the **top loop contribution**.
- Including top loop lowers $\sigma_{gb \rightarrow bh}$ by **15%(10%)** at the Tevatron (LHC)

Results for Semi-inclusive $b(\bar{b})h$ Production ...again



(from S. Dawson, C.J., L. Reina and D. Wackeroth (2004), hep-ph/0408077)

MSSM Semi-Inclusive $b(\bar{b})H^0$



- For $\tan \beta = 40$, top loop contribution $\leq 0.08\%$ in $gb \rightarrow bh$

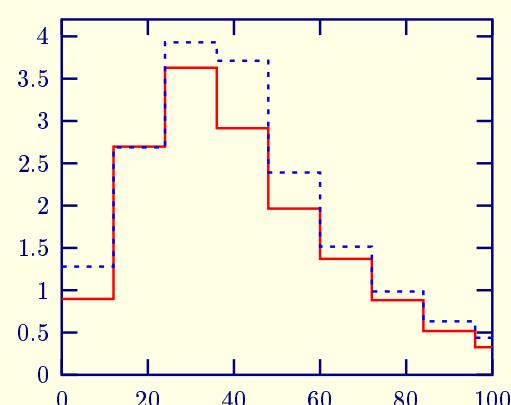
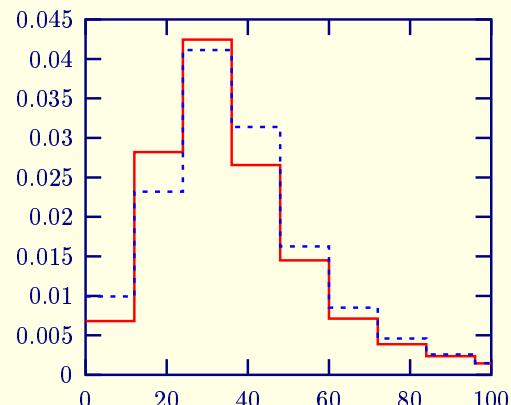
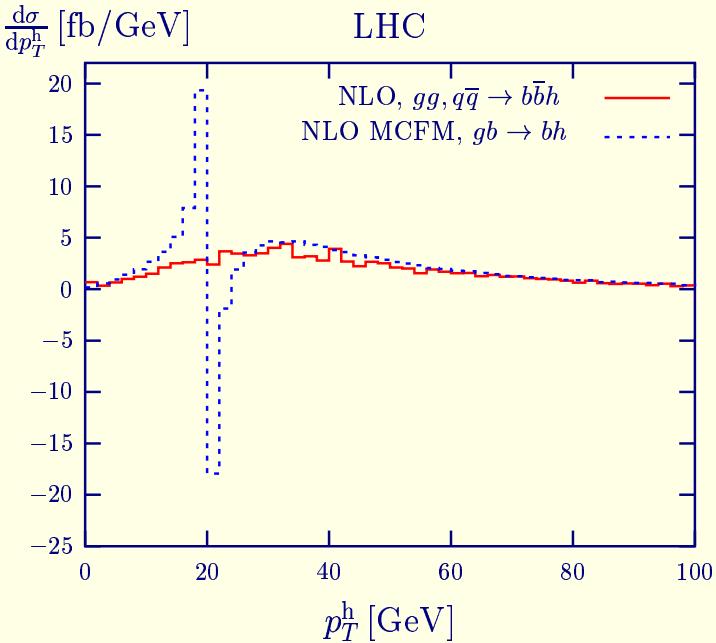
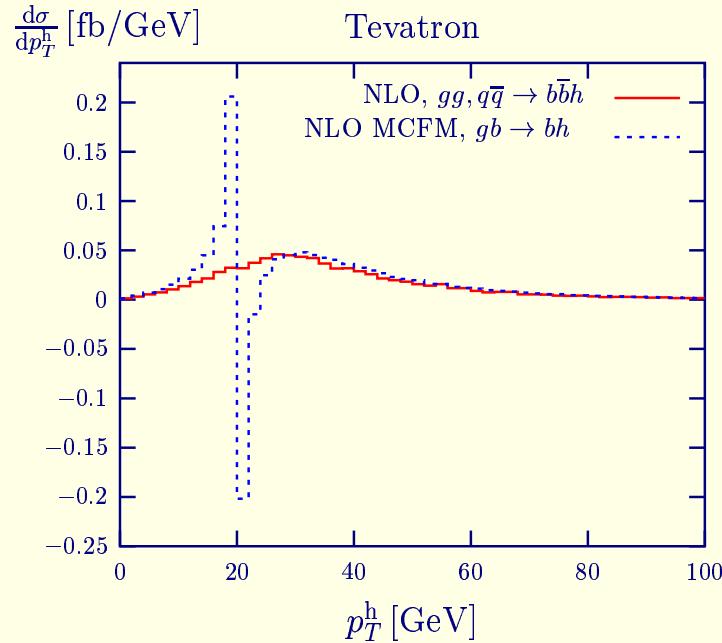
Summary

- $b\bar{b}h$ can play **important role** in Higgs production at Hadron Colliders for models w/ enhanced b quark Yukawa couplings (e.g. 2HDM, MSSM)
- QCD corrections can have **large effects** on distributions and drastically reduce theoretical uncertainties
- **Exclusive Production:** agreement between two independent NLO QCD calculations
- **Inclusive Production:** “good” agreement between 4FNS and 5FNS calculations (**top loop diagrams?**)
- **Semi-inclusive Production:**
 - **Academically:** SM results now agree (**spectacularly!**) between 4FNS and 5FNS after the inclusion of the top loop diagrams in $gb \rightarrow bh$
 - **Numerically:** MSSM results agree between 4FNS and 5FNS

Further Reading

- Exclusive Production:
 - S. Dittmaier, M. Kramer, M. Spira (hep-ph/0309204)
 - S. Dawson, C.J., L. Reina, D. Wackerlo (PRD 69 074027 (2004))
- Inclusive and Semi-inclusive Production:
 - Harlander and Kilgore (PRD 68 013001(2003))
 - J. Campbell et. al. (PRD 67 095002 (2003))
- Comparison between 4FNS/5FNS:
 - LH HWG (hep-ph/0405302)
 - S. Dawson, C.J., L. Reina and D. Wackerlo , hep-ph/0408077

p_T Distributions for Semi-inclusive Production



(from S. Dawson, C.J., L. Reina and D. Wackeroth (2004), hep-ph/0408077)

“Divergences” in p_T Distributions

- Similar effects seen in Drell-Yan Q_\perp distributions (for review, see S. Catani and B.R. Webber, hep-ph/9710333)
- At LO, Higgs **recoils** against b jet:
 - p_T cut on b jet \implies **cut on p_T^h**
 - $(\frac{d\sigma}{dp_T^h})_{LO} \rightarrow$ “**non-smooth**” function
- In the region of the “cut” on p_T^h , the NLO c.s. is the convolution of the LO c.s. with a “**soft gluon probability**”
 - ”Soft gluon probability” \rightarrow “plus” distribution
“non-smooth” $f(z) = \int_0^1 dz f(z)[g(z)]_+$ = “**logarithmic divergences**”
- Improvement through **resummation techniques** (see, e.g. N. Kidonakis, hep-ph/9902484)